Part IV

Summary of Physics reach

Chapter 17

Summary of Physics Reach and Comparisons With Other Experiments

17.1 Sensitivities to CP Violating Angles

BTeV will have outstanding performance in determining CP violating asymmetries. The results of our simulations are summarized in Table 17.1 for a luminosity of 2×10^{32} cm^{-2}s^{-1} and 10^7 seconds.

Table 17.1: Yearly sensitivities for CP violating quantities.

Quantity	Decay Mode(s)	Sensitivity
$\sin(2\beta)$	$B^o \to J/\psi K_S$	± 0.025
α	$B^o \to \rho\pi$	$\sim \pm 10°$
γ	$B_s \to D_s^{\pm} K^{\mp}$	$\sim \pm 7°$
γ	$B^- \to \overline{D}^o K^-$	$< \pm 10°$
γ	$B \to K\pi$	$\pm < 5°$ (plus theoretical errors)
$\sin(2\chi)$	$B_s \to J/\psi\eta^{(\prime)}$	± 0.033
Asymmetry	$B^o \to \pi^+\pi^-$	± 0.024

We briefly discuss each of these measurements:

- The error in $\sin(2\beta)$ includes the 20% improvement (over a time-integrated measurement) we obtain by fitting the time distribution.

- We expect to have $\sim$1000 effective flavor tagged $\rho^{\pm}\pi^{\mp}$ events and $\sim$150 $\rho^o\pi^o$ per year. The signal/background levels are 4.1 and 0.3, respectively. We have not done a full simulation of our sensitivity to α. Final results will depend on several unknown quantities including the branching ratio for $\rho^o\pi^o$, and the ratio of tree to penguin amplitudes.

Analysis by Snyder and Quinn [1] showed that with 2000 background free events they always found a solution for α and the accuracy was in the range of 5-6°. We can collect these events in 2×10^7 seconds, but we will have some background. Furthermore Quinn and Silva have proposed using non-flavor-tagged rates as input that should improve the accuracy of the α determination [2].

- Although the $B \to K\pi$ modes provide the smallest experimental error in determining γ, there is model dependent error associated with this method. On the other hand, the other two methods, which use $B_s \to D_s^\pm K^\mp$ and $B^- \to \overline{D}^o K^-$, provide model independent results and can be averaged. The interplay of the three methods can be used to resolve ambiguities.

- The error in $\sin(2\chi)$ averaged over both $J/\psi\eta$ and $J/\psi\eta'$ decay modes of the B_s is $\pm 3.3\%$, using only $J/\psi \to \mu^+\mu^-$ decays. Since we expect an asymmetry of $\sim 3\%$, it will take us a few years to make this important measurement. Including $J/\psi \to e^+e^-$ and $B_s \to J/\psi\phi$ would reduce the time.

- The asymmetry in $B^o \to \pi^+\pi^-$ may be useful to gain insight into the value of α with theoretical input or combined with $B_s \to K^+K^-$ and theory to obtain γ. This study was done both with MCFast and GEANT. The signal efficiency is 10% higher in MCFast and the background levels the same in both, within statistics.

17.2   Sensitivity to B_s Mixing

BTeV can definitively reach x_s values of 75 in 10^7 seconds of running. Put another way, it will take us only 5 days of steady running to reach x_s of 20. These estimates are based on the decay mode $B_s \to D_s^+\pi^-$, with $D_s^+ \to \phi\pi^+$ and $K^{*o}K^+$. Definitive is defined here as the ability to make a measurement where the best solution for a fit to the oscillation frequency is better by "5 standard deviations" than the next best fit. Thus BTeV can cover the entire range of x_s values allowed in the Standard Model.

17.3   Reach in Rare Decays

BTeV has excellent reach in rare decays. We have investigated the exclusive decays $B^o \to K^{*o}\mu^+\mu^-$, $B^+ \to K^+\mu^+\mu^-$ and the inclusive decay $B \to X_s\mu^+\mu^-$.

We acquire ~ 2200 $K^{*o}\mu^+\mu^-$ decays in 10^7 seconds, enough to measure the lepton-forward-backward asymmetry and test the Standard Model. Although the asymmetry is expected to be small in $K^+\mu^+\mu^-$, we test the Standard Model expectation, due to our large sample of ~ 1300 events per year.

We also expect to be able to measure the inclusive rate $b \to s\mu^+\mu^+$ with 20σ significance. This inclusive rate is very important. It could either show non-Standard Model physics or greatly constrain alternative models.

17.4 Comparison with CDF, D0, CMS, and ATLAS

Both CDF and D0 have measured the b production cross section [3]. CDF has contributed to our knowledge of b decay mostly by its measurements of the lifetime of b-flavored hadrons [4], which are competitive with those of LEP [5] and recently through its discovery of the B_c meson [6]. CDF has also seen the first hint for CP violation in the b system [7]. These detectors were designed for physics discoveries at large transverse momentum. It is remarkable that they have been able to accomplish so much in b physics. They have shown that it is possible to do b physics in the environment of a hadron collider.

However, these detectors, and the new central detectors ATLAS and CMS are very far from optimal for b physics. BTeV has been designed with b physics as its primary goal. To have an efficient trigger based on separation of b decays from the primary, BTeV uses the large $|\eta|$ region where the b's are boosted. The detached vertex trigger allows collection of interesting purely hadronic final states such as $\pi^+\pi^-$, $\rho\pi$, $D_s^+\pi^-$ and $D_s^+K^-$. It also allows us to collect enough charm to investigate charm mixing and CP violation.

The use of the forward geometry also allows for excellent charged hadron identification over a wide momentum range, with a gaseous RICH detector. This is crucial for many physics issues such as separating $K\pi$ from $\pi\pi$, $D_s\pi$ from D_sK, kaon flavor tagging, etc.

Furthermore an experiment that plans on answering all the open questions in b physics, requires a high quality electromagnetic calorimeter. Installation of such a calorimeter in the CLEO detector made new physics vistas possible and such a device in BTeV allows for the measurement of several crucial final states such as $B^o \to \rho\pi$, and $B_s \to J/\psi\eta'$. The only central detector that is planning to have a high quality electromagnetic calorimeter is CMS.

Finally, BTeV has all the crucial elements required to study any newly suggested b or charm process or uncover new physics. The crucial elements are:

- a detached vertex trigger in the first trigger level,

- highly efficient particle identification across the entire momentum range with good ($\approx$ 100:1) background rejection,

- an electromagnetic calorimeter with sufficiently good energy resolution and efficiency to fully reconstruct rare B decay final states with single photons or neutral pions.

BTeV will have a physics reach substantially beyond that of CDF, D0, CMS, and ATLAS.

17.5 Comparison with e^+e^- B Factories

Most of what is known about b decays has been learned at e^+e^- machines [8]. Machines operating at the $\Upsilon(4S)$ found the first fully reconstructed B mesons (CLEO), B^o-$\overline{B}^o$ mixing (ARGUS), the first signal for the $b \to u$ transition (CLEO), and Penguin decays (CLEO). Lifetimes of b hadrons were first measured by experiments at PEP, slightly later at PETRA, and extended and improved by LEP [8].

The success of the $\Upsilon(4S)$ machines has led to the construction at KEK and SLAC of two new $\Upsilon(4S)$ machines with luminosity goals in excess of $3 \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$. These machines will have asymmetric beam energies so they can measure time dependent CP violation. They will join an upgraded CESR machine at Cornell that has symmetric beam energies. These machines will investigate only B^o and $B^{\pm}$ decays. They will not investigate B_s, B_c or Λ_b decays [9].

Table 17.2 shows a comparison between BTeV and an asymmetric e^+e^- machine for measuring the CP violating asymmetry in the decay mode $B^o \to \pi^+\pi^-$. Here we use the recently reported measurement of the branching ratio by CLEO [10]. In Table 17.3 we show a similar comparison for the final state $B^- \to \overline{D}^o K^-$, a mode that could be used to determine the CKM angle γ. It is clear that the large hadronic b production cross section can overwhelm the much smaller e^+e^- rate. Furthermore, the e^+e^- B factories do not have access to the important CP violation measurements that need to be made in B_s decays.

Table 17.2: Number of tagged $B^o \to \pi^+\pi^-$ ($\mathcal{B}{=}0.43 \times 10^{-5}$).

	$\mathcal{L}(\text{cm}^{-2}\text{s}^{-1})$	σ	# $B^o/10^7$ s	Signal Efficiency	Tagging ϵD^2	# tagged/10^7 s
e^+e^-	3×10^{33}	1.2 nb	3.6×10^7	0.3	0.3	13
BTeV	2×10^{32}	100μb	1.5×10^{11}	0.037	0.1	2370

Table 17.3: Number of $B^- \to \overline{D}^o K^-$ ($\mathcal{B}{=}1.7 \times 10^{-7}$).

	$\mathcal{L}(\text{cm}^{-2}\text{s}^{-1})$	σ	# $B^-/10^7$ s	Signal Efficiency	Events/10^7 s
e^+e^-	3×10^{33}	1.2 nb	3.6×10^7	0.5	2
BTeV	2×10^{32}	100μb	1.5×10^{11}	0.012	300

17.6 Comparison with LHC-b

17.6.1 General Comparisons

LHC-b [11] is an experiment planned for the LHC with almost the same physics goals as BTeV. Here we show how BTeV can compete with LHC-b in many areas and why it is a superior experiment in some very important areas. Both experiments intend to run at a luminosity of 2×10^{32} cm^{-2}s^{-1}. There are several inherent advantages and disadvantages that LHC-b has compared with BTeV. The issues that favor LHC-b are:

- The b production cross-section is expected to be about five times larger at the LHC than at the Tevatron, while the total cross-section is only 1.6 times as large.

- The mean number of interactions per bunch crossing is expected to be about 3 times lower at the LHC than at the Tevatron (at 132 ns bunch spacing).

The issues that favor BTeV are:

- BTeV is a two-arm spectrometer, which increases the signal by a factor of two compared with LHC-b.

- The short bunch spacing at the LHC, 25 ns, has serious negative effects on all their detector subsystems. There are occupancy problems if the sub-detector integration times are long. This can be avoided by having short integration times, but that markedly increases the electronics noise. For example, in a silicon detector these considerations make first level detached vertex triggering more difficult than at the Tevatron; BTeV has a more relaxed 132 ns bunch spacing, 5.3 times longer. In fact, the current plan of LHC-b is to trigger in their first trigger level on muons, electrons or hadrons of moderate p_t, and detect detached vertices in the next trigger level.

- The seven times larger beam energy at the LHC makes the range of track momenta that need to be momentum analyzed and identified much larger and therefore more difficult. The larger energy also causes a large increase in track multiplicity per event, which makes pattern recognition and triggering more difficult.

- The interaction region at the Tevatron is three to six times longer along the beam direction than at LHC ($\sigma_z = 5$ cm), which allows BTeV to be able to accept collisions with a mean of two interactions per crossing, since the interactions are well separated in z. LHC-b plans to veto crossings with more than one interaction.

- BTeV is designed to have the vertex detector in the magnetic field, thus allowing the rejection of low momentum tracks at the trigger level. Low momentum tracks are more susceptible to multiple scattering which can cause false detached vertices leading to poor background rejection in the trigger.

- BTeV is designed with a high quality $PbWO_4$ electromagnetic calorimeter, that provides high resolution and acceptance for interesting final states with γ's, π^o's, and $\eta^{(')}$'s.

- Use of a detached vertex trigger at Level 1 allows for an extensive charm physics program absent in LHC-b. It also allows for a more uniform collection of b triggers.

- The LHC-b data acquisition system is designed to output 200 Hz of b decays, while BTeV is designed for a 4,000 Hz output bandwidth where we estimate 1,000 Hz of b's and 1,000 Hz of charm; BTeV potentially has access to a much wider range of heavy quark decays.

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- The BTeV electromagnetic calorimeter is superior in energy resolution and segmentation to LHC-b's. BTeV uses PbWO$_4$ crystals while LHC-b has a Shaslik-style Pb-scintillating fiber device, following a preshower detector. The LHC-b energy resolution is $10\%/\sqrt{E} \oplus 1.5\%$, which compares poorly with BTeV's $1.6\%/\sqrt{E} \oplus 0.55\%$. The LHC-b detector segmentation is 4 cm × 4 cm up to ~90 mr, 8 cm × 8 cm to ~160 mr and 16 cm × 16 cm at larger angles. (The distance to the interaction point is 12.4 m.) Thus the segmentation is comparable to BTeV only in the inner region. (BTeV has 2.6 cm × 2.6 cm crystals 7.4 m from the center of the interaction region.)

We have more than compensated for LHC-b's initial advantages in b cross-section due their higher center-of-mass energy. In fact, the high energy actually works in many ways as a disadvantage. For example, LHC-b needs two RICH counters to cover the momentum range in their one arm. Particle identification and other considerations force LHC-b to be longer than BTeV. Its single arm is as long as both BTeV arms put together. As a result, LHC-b's transverse size is four times that of BTeV, but it covers the same solid angle as only one of BTeV's two arms. It is expensive to instrument all of this real estate with high quality particle detectors. Thus, the total cost for LHC-b based only on instrumented area, (a naive assumption) would be twice the total cost for BTeV, even though LHC-b would cover only half the solid angle.

We have done a detailed comparison between BTeV and LHC-b using two modes of great importance because they give direct determinations of the CP violating angles α and γ, and report our results here.

17.6.2 $B^o \rightarrow \rho\pi$

We base our comparison on the total number of untagged events quoted by both experiments. The BTeV numbers come from Part III of this document. The LHC-b numbers are found in their Technical Design Report [11]. Both sets of numbers are calculated for 10^7 seconds at a luminosity of 2×10^{32} cm^{-2}s^{-1}. We have corrected the LHC-b numbers by normalizing them to the branching ratios used by BTeV. In Table 17.4 we compare the relevant quantities [12].

Table 17.4: Event yields and signal/background for $B^o \rightarrow \rho\pi$.

Mode	Branching Ratio	BTeV Yield	S/B	LHC-b Yield	S/B
$B^o \rightarrow \rho^{\pm}\pi^{\mp}$	2.8×10^{-5}	9400	4.1	2140	0.8
$B^o \rightarrow \rho^o\pi^0$	0.5×10^{-5}	1350	0.3	880	-

LHC-b has done a background estimate based on a heavily preselected sample of events [13]. These include:

- a preselection for charged pions and photons which required the momentum or energy to exceed a value depending on the polar angle of the candidate. For charged pions, the momentum cut varied between 1 and 2 GeV/c and for photons the energy cut varied between 2 and 6 GeV;

- selection of signal-like events based on a discriminant variable built from kinematic variables of the π, ρ and B^o;

- selection based on the reconstructed secondary vertex for a $\pi^+\pi^-$ combination;

- Dalitz plot cuts to eliminate low energy π^o combinatorial background due to particles from the primary vertex.

These cuts are applied to the generator event sample before the events are processed through GEANT [14]. The BTeV simulation was carried out without any preselection cuts. We were worried that the preselection would bias us to lower background rates. For example, if two photons overlapped or interactions of charged tracks put energy into photon clusters these can well become part of our background sample. Thus the LHC-b background estimate may well be only a lower limit.

We note that their π^o mass resolution varies between 5 and 10 MeV/c^2 (r.m.s.) and their B^o mass resolution is 50 MeV/c^2 (r.m.s.). The corresponding numbers for BTeV are 3.1 MeV/c^2 and 28 MeV/c^2.

With this analysis, LHC-b claims signal/background (S/B) of 1.3 for $\rho^\pm\pi^\mp$, where they have assumed a branching ratio of 4.4×10^{-5}. For our assumed branching ratio, S/B is 0.8; The S/B for BTeV is 4.1. Furthermore, the BTeV background analysis was done without preselection and therefore is likely to be more realistic. For the final state $\rho^o\pi^o$ LHC-b has not produced a background estimate; in our experience it is difficult to estimate signal efficiencies without evaluating how restrictive the selection criteria need to be to reduce backgrounds.

It is not surprising that BTeV's superior crystal calorimeter and detached vertex trigger produce a large advantage in this final state over LHC-b. BTeV has a factor of 7 advantage in signal yield in $\rho^\pm\pi^\mp$ and a better S/B by a factor of 5.

17.6.3 $B_s \to D_s^\pm K^\mp$

A comparison of the estimated total efficiencies (excluding D_s decay branching ratios), B_s mass resolutions, and S:B ratios are given in Table 17.5. Here $D_s^+ \to K^+K^-\pi^+$ can be reconstructed via either $\phi\pi^+$ or $K^{*o}K^-$. Here BTeV and LHC-b differ somewhat. LHC-b has the same efficiency in both modes, whereas BTeV analyzes them somewhat differently. For $K^{*o}K^-$ BTeV requires both charged kaons to hit the RICH detector, while for $\phi\pi^+$ only one charged kaon is required to be identified in the RICH. (The reconstruction efficiency for $\phi\pi^+$ is 4.5%, while for $K^{*o}K^-$ it is 2.5%).

We are a factor of 1.7 better in this mode. This is not unexpected. The LHC-b trigger efficiency is 4.1 times lower than BTeV and their acceptance a factor of two lower, since BTeV has two arms and the apertures of the two experiments are nearly equal. This factor

Table 17.5: Comparison of BTeV and LHC-b sensitivities for $B_s \rightarrow D_s^{\pm} K^{\mp}$.

Branching Ratio	BTeV		LHC-b	
	Yield	S/B	Yield	S/B
3×10^{-4}	13,100	7	7,660	7

of 8 should more-than neutralize the LHC-b cross-section advantage, of a factor of 5, and in this study it has. We note however, that details of the analysis come into play. If we require both kaons from the ϕ to hit the RICH, we reduce our number of events to 9550, still 1.25 times larger than LHC-b.

17.7 Summary

BTeV is far superior to e^+e^- colliders operating on the $\Upsilon(4S)$ because of the enormous difference in the b rate. For reconstructed B^+ and B^o decays, BTeV has a factor of $\sim$200 more rate. Furthermore, the important B_s physics cannot be done at the e^+e^- machines [9].

CDF, D0, CMS, and ATLAS cannot compete in areas where particle identification or photon detection are important; as a result, the b-physics reach of BTeV is substantially greater.

BTeV is competitive with LHC-b in 'high-priority' final states with all charged particles. For final states with γ's, π^o's, η's or η''s, BTeV has a factor of $\approx$7 advantage. Furthermore, BTeV will write to tape a factor of 5 more b events than LHC-b, allowing for more physics studies.

BTeV has all the components necessary to measure the most important quantities in heavy quark decays. These include spectacular vertex detection, triggering, particle identification, photon detection, and electron and muon identification. The studies presented here were done on what is currently believed to be the most important modes. What's in fashion, however, changes. BTeV is a powerful enough detector to be able to test new and interesting ideas.

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[8] See *B Decays, revised 2nd Edition* ed. S. Stone, World Scientific, Singapore, (1994).

[9] In principle the e^+e^- machines could run on the $\Upsilon(5S)$, which is likely to be a source of B_s mesons. However, the predicted cross-section for B_s production is only ~ 0.1 of that of B production on the $\Upsilon(4S)$. Furthermore the decay time resolution necessary to resolve B_s oscillations cannot be obtained using the relatively slow B_s mesons produced at the $\Upsilon(5S)$.

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[11] "LHCb Technical Proposal," CERN/LHCC 98-4, LHCC/P4 (1998), available at http://lhcb.cern.ch .

[12] We have confirmed with T. Nakada, the LHC-b spokesperson, that the yields for this mode as quoted in their Technical Proposal are their current values that we should use in our comparisons. The branching ratio numbers used by LHC-b were taken from Table 15.11 on page 157. The number of events were taken from Table 15.12. Since these numbers are quoted as being "tagged," we divided by the 0.40 tagging efficiency given on page 145. The two final states $\rho^+\pi^-$ and $\rho^-\pi^+$ are given separately by LHC-b; we added them together. The same proceedure was followed for $B_s \to D_s K$.

[13] P. Ball *et al.*, "*B* Decays at the LHC," CERN-TH/2000-101, hep-ph/0003238.

[14] Although they state a 1% efficiency here, this is only a partial efficiency according to T. Nakada.